



A New Two-Stage Approach to predicting the soil water characteristic from saturation to oven-dryness



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SUMMARY

The present study proposes a new two-step approach to prediction of the continuous soil water characteristic (SWC) from saturation to oven-dryness from a limited number of measured textural data, organic matter content and dry bulk density. The approach combines dry- and wet-region functions to obtain the entire SWC by means of parameterizing a previously developed continuous equation. The dry region function relates gravimetric soil fractions to adsorptive forces and the corresponding water adsorbed to soil particles. The wet region function converts the volumetric particle size fractions to pore size fractions and utilizes the capillary rise equation to predict water content and matric potential pairs. Twenty-one Arizona source soils with clay and organic carbon contents ranging from 0.01 to 0.52 kg kg⁻¹ and 0 to 0.07 kg kg⁻¹, respectively, were used for the model development. The SWCs were measured with Tempe cells, a WP4-T Dewpoint Potentiometer, and a water vapor sorption analyzer (VSA). The model was subsequently tested for eight soils from various agricultural fields in Denmark with clay contents ranging from 0.05 to 0.41 kg kg⁻¹. Test results clearly revealed that the proposed model can adequately predict the SWC based on limited soil data. The advantage of the new model is that it considers both capillary and adsorptive contributions to obtain the SWC from saturation to oven-dryness.

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1. Introduction

The soil water characteristic (SWC) relates the water content and the matric potential of a soil. The SWC is key for studying various soil water related processes such as water availability for plants, evapotranspiration, and modeling of water and gas flow in partially saturated soils. The SWC is highly non-linear and can be directly measured in the laboratory or field, or be predicted from soil properties with pedotransfer functions. Measurements of the SWC across a wide range of matric potentials are laborious due to long equilibration times, thus rendered impractical for many applications. Numerous empirical parametric models have consequently been proposed with the Brooks and Corey (1964) and the van Genuchten (1980) equations being the most commonly applied in soil and porous media research. Soil water characteristic measurements are primarily conducted for matric potentials above –1500 kPa or below pF 4.2 (where pF is the common logarithm of the absolute matric potential in cm) due to reduced accuracy and longer equilibration times at low matric

potentials (Bittelli and Flury, 2009). The longer equilibration time is a consequence of adsorptive surface forces governing the dry region of the SWC, which are stronger than the capillary forces that dominate the wet region of the SWC (Tuller et al., 1999).

Measurements of the SWC under dry conditions may, however, now be achieved faster and with higher accuracy using the well-established, dew point technique, which enables measurement of the vapor pressure of soil air in equilibrium with the matric potential (Gee et al., 1992). This method has been used to measure the dry-end SWC for six soils with textures ranging from sandy to silty clay (Campbell and Shiozawa, 1992), where a linear relationship between the water content and the logarithm of the matric potential above pF 4 was established. This classical dataset has been used in several other studies (e.g. Fayer and Simmons, 1995; Khlosi et al., 2006; Webb, 2000), who all used a linear approach to describe the soil water characteristic. These models were later evaluated by Lu et al. (2008), who also measured the dry-end SWC for eight soils by means of the chilled mirror dewpoint technique. The fairly rapid and accurate methods available for measuring the energy state and water content under dry conditions have resulted in several recent studies presenting new dry-end SWC data and establishing that intimate relationships exist between

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the dry-end SWC and clay content (Arthur et al., 2014a; Chen et al., 2014; Schneider and Goss, 2012a; Wuddivira et al., 2012; Wäldchen et al., 2012), and soil specific surface area (Arthur et al., 2013; Leão and Tuller, 2014; Resurreccion et al., 2011). The availability of such relationships in the dry SWC range provides the basis for the development of a model that can predict the water content associated to different matric potentials in the dry region.

Because there has been a general lack of measured dry-end SWC data there is a lack of models to predict the entire SWC from saturation to oven-dryness, for all textural soil classes. Most existing SWC models can be applied with varying success for wet conditions, depending on texture, and they usually have restricted applicability in the dry region (Khlosi et al., 2008). Suggestions have consequentially been made to obtain the SWC by parameterizing the van Genuchten (1980) model and extending it linearly throughout the dry region to oven-dryness (e.g. Schneider and Goss, 2012b; Webb, 2000).

Recent studies have shown that there is a relationship between the pore size distribution, which is linked to the SWC, and the volumetric soil size fractions including organic matter (Moldrup et al., 2007; Naveed et al., 2012). However, these studies only analyzed sandy and loamy soils and did not include the dry region of the SWC and further noted that more research on the topic would be necessary.

The objective of the presented study was to develop a robust model that predicts the entire SWC from saturation to oven-dryness for all soil textural classes based on texture, organic matter content, and bulk density. The model parameters were determined based on 21 differently textured soils and the model thereafter validated for data of eight independently measured soils. The proposed new approach uses a combination of volumetric and gravimetric texture size fractions to predict the wet and dry regions of the SWC, respectively. The model predicts 10 matric potential and water content pairs that are subsequently used to parameterize a previously developed continuous equation that captures the SWC from saturation to oven-dryness.

2. Model development

The forces governing the retention of water within the soil matrix are capillary and adsorptive surfaces forces. While the adsorptive surfaces forces govern the dry region, the capillary forces dominate the wet region (Or and Tuller, 1999; Tuller et al., 1999). Common measurements of the SWC are usually conducted at matric potentials below pF 4.2 (>–1500 kPa) (Lu et al., 2008), and this study therefore used pF 4.2 to separate the dry and wet region. Since the dry and wet regions are dominated by different forces, two models capturing the wet- and dry-ends of the SWC are proposed to predict equilibrium matric potential-volumetric water content pairs that are subsequently used to parameterize a continuous SWC equation.

2.1. Dry-region model

A linear relationship between pF and the water content between pF 4 and pF 7 where pF 7 is oven-dryness, was introduced by Campbell and Shiozawa (1992) based on six soils with clay contents ranging from 0.05 to 0.47 kg kg⁻¹. Later it was recommended that pF 6.9 should be applied instead of pF 7 as the matric potential for oven-dry conditions (Arthur et al., 2013; Groenevelt and Grant, 2004).

The water content in the dry SWC range is governed by adsorptive forces, and hence controlled by the specific surface area. The specific surface area is primarily governed by the quantity of fines (clay, organic matter and silt). Due to the relation between fines

and adsorption, studies have related the gravimetric water content at a specific relative humidity (RH) to the clay content for a wide range of soil types and clay minerals (Arthur et al., 2014a; Chen et al., 2014; Wuddivira et al., 2012; Wäldchen et al., 2012). Organic matter significantly contributes to water adsorption, particularly in soils with low clay contents that are not considered hydrophobic (Arthur et al., 2014a). It was also shown that the weighting factor for organic matter (OM) is twice that of the clay content for soils with water contents at pF 4.2 based on measured data of 41 soils (Hansen, 1976). The large surface areas of clay and OM are expected to have the largest influence on water adsorption, but silt can likewise have a significant effect on water adsorption, especially for soils with high silt and low clay contents.

If linearity between pF and water content can be assumed, it is possible to develop a model to predict the water content in the dry region by using a single reference point. In this study pF 6 (~50% RH) was used as a reference point, and assuming a weighting factor of 2 for OM, a regression model for the volumetric water content (cm³ cm⁻³) at pF 6 (θ_{pF6}) can be proposed as:

$$\theta_{pF6} = A(CL + 2 OM + B S)\rho_b \quad (1)$$

where CL, S, and OM are the clay, silt and organic matter contents (kg kg⁻¹), respectively, ρ_b is the dry bulk density (g cm³), and A and B are free model parameters, where A has units of cm³ g⁻¹. The best-fit model parameters A and B are determined and evaluated in the results and discussion section based on measured data. We propose a new linear dry-region model for $\theta(\psi)$ when θ_{pF6} is known or obtained from Eq. (1), by adopting the linearity concept for the dry region with the matric potential at oven-dryness assumed at pF 6.9:

$$\theta(-\psi) = \frac{\theta_{pF6} (6.9 - \log_{10}(-\psi))}{6.9 - 6} \quad (2)$$

where ψ is the matric potential (cm H₂O) and θ is the volumetric water content (cm³ cm⁻³). The value of 6.9 is the pF at oven-dryness, and 6 is the pF value of the known or predicted water content.

2.2. Wet-region model

The wet region soil water retention is primarily governed by capillary forces that are described by the well-known Young-Laplace equation. In simple terms, the Young-Laplace equation can be approximated to be a relation between the matric potential and the pore size (Hillel, 1980):

$$-\psi = \frac{3000}{d} \quad (3)$$

where d is the pore diameter (μm) and ψ is capillary rise equivalent to the matric potential (cm). In such system the pore diameter is linked to the particle size, with the coarse particles generating the biggest pores and the fine particles generating the smallest pores. Since Eq. (3) is controlled by capillarity, and Tuller et al. (1999) showed that for loamy soils the adsorptive forces dominate capillary forces at pF 3, Eq.(3) was not applied for potentials higher than pF 3 to alleviate prediction errors.

The mean pore diameter was found to be approximately 30% of the mean particle diameter, based on experimental data of sandy and loamy soils (Hamamoto et al., 2011; Sakaki et al., 2014). The proposed model in this subsection was thus derived based on Eq. (3) with $d = 0.3D$, where D is the mean particle diameter. As an example, a soil matrix exhibiting a matric potential of –20 cm H₂O (pF 1.3) will, in equilibrium, have drained the pores >150 μm , or what corresponds to pore fractions formed by the particles >500 μm (coarse sand). Assuming Eq. (3) is valid for a soil matrix and $d = 0.3D$, the pores generated by different soil particle size fractions can be separated into different groups. For example,

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